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EFFECT OF THERMAL CYCLING ON ZrO_2-Y_2O_3 THERMAL BARRIER COATINGS

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INTRODUCTION

Ceramic coatings applied to the heated side of internally cooled hot-section components of gas turbine engines permit increased efficiency through use of higher gas temperature or less cooling air, or extended component life by reducing metal temperature (refs. 1 to 3). Extensive research has improved thermal barrier coating (TBC) durability, (refs. 4 to 6). Extended performance under cyclic heating is essential if TBCs are to be used in aircraft or utility turbine engines (ref. 7).

Heating of a zirconia TBC produces thermal gradients and stresses which persist in a cooled system. Additional stresses arise from thermal expansion mismatch with higher expansion superalloy substrates. Stresses are compressive at ambient temperature if the alloy is heated during coating application. During operation at high temperature, tensile stresses arise in the zirconia. The purpose of this study was to determine the effect of short and long duration heating cycles on ZrO_2-Y_2O_3 coatings, the cause of any cycle frequency effects, and methods to improve tolerance to thermal stress.

EXPERIMENTAL PROCEDURE

Materials and Coating Procedure

Solid Rene' 41 rods 1.3 cm in diameter were coated with Ni-Cr-Al-Y bond coat and ZrO_2-Y_2O_3 ceramic by first grit blasting with Al_2O_3 and then plasma spraying in air with a 0.013 mm Ni-18Cr-12Al-0.3Y or Ni-16Cr-6Al-0.3Y bond coat. The specimens were then coated with 0.038 mm of zirconia prealloyed with either 8 or 12 w/o Y_2O_3.

Apparatus and Test Procedure

The coated rods were evaluated by heating eight specimens in a rotating carousel with a 0.3 Mach burner flame. Gas temperture was approximately 1450° C. Steady state metal temperature was 1040° C. The specimens were heated either for 4 minutes followed by 3 minutes of forced cooling, or for 57 minutes followed by 3 minutes of forced cooling. The condition of the ceramic coating was determined by visual inspection. The fuel was Jet A-1.

The burner was moved by a pneumatic cylinder to impinge on the specimens in less than one second. Measurements of temperature rise after impingement

of the flame were made with a thermocouple approximately 0.26 mm under the bond coat.

RESULTS AND DISCUSSION

Experimental Results

The results of cyclic heating of a total of 24 ceramic coated bars in the 0.3 Mach flame are shown in figure 1(a). The short heating cycle sharply reduced coating life in terms of time at temperature for all four TBCs.

The cycles to fail the ceramic coatings are plotted against heating time per cycle in figure 1(b). For specimens with a bond coat of Ni-16Cr-6Al-0.3Y, the failure was at constant cycles and was independent of the heating time per cycle. Coating lives in terms of either cycles or time to failure were longer with Ni-18Cr-12Al-0.3Y bond coat than with Ni-16Cr-6Al-0.3Y. However, long heating cycles reduced the lives of ZrO_2/Ni-18Cr-12Al-0.3Y coatings in terms of cycles to failure. ZrO_2-8w/oY_2O_3 and ZrO_2-12w/oY_2O_3 performed about the same.

Analysis

To determine if thermal stress was producing the strong decrease in life of the coating caused by cycling, thermal gradients and thermal stresses in the coating were calculated by both a short method and by numerical analysis.

<u>Short method of calculating thermal stress</u>. - The thermal stress in the ceramic coating is

$$\sigma = \frac{\sigma E \Delta T}{2(1 - \mu)}$$

where

$$\Delta T = \frac{\dot{Q}}{A}\frac{t}{k}$$

This stress can be equated to the hoop stress in the ceramic,

$$\sigma = \frac{Pd}{2t},$$

where: P is the attachment strength of the ceramic to the specimen; σ = stress; ΔT = temperature difference; $\dot{Q}$ = heat input; A = heated area; and t = ceramic coating thickness, 0.038 cm. Additional terms and ceramic properties are: μ = Poisson's ratio, 0.25; E = elastic modulus, 4.8×10^4 MPa; α = coefficient thermal expansion, $7.6 \times 10^{-6}/^\circ C$; k = thermal conductivity, 6.9×10^{-2} cm-kw/m^2 - °C. Based on the properties of plasma sprayed zirconia, P = 8.0×10^{-3} $\dot{Q}/A$. The maximum $\dot{Q}/A$ was empirically determined from the rate of temperature rise of the coated rod as measured from the instant at which heating starts in the 0.3 Mach flame. This value of

$$5.5\times10^2 \frac{kW}{m2}$$

yields a value $P = 4.4$ MPa. For typical plasma sprayed coatings, P has an average value of 6.2 MPa, but this average includes values as low as 3.7 MPa (ref. 4). Thus, this simple calculation shows that heating rates in the 0.3 Mach flame give stresses which are close to the attachment strength of ZrO_2-Y_2O_3 to the bond coat.

Numercial analysis. - A transient heat transfer analysis was made with the SINDA program (refs. 8 and 9). The average heat transfer coefficient, h_g, was calculated using free stream conditions, (refs. 10 and 11). Typical time-temperature profiles are shown in figure 2(a) for a 0.13 mm NiCrAlY and 0.38 mm ZrO_2-Y_2O_3 coating on a 1.3 cm diameter stainless steel or Rene' 41 rod.

Thermal stresses were calcualted by combining the SINDA output with the program FEATS, (refs. 12 and 13). Typical time-stress profiles for the elastic case are shown in figure 2(b). Longitudinal and hoop stresses are compressive in the 0.38 mm coating and larger than the tensile strength of ZrO_2-Y_2O_3 (56 MPa). However, they would remain within the allowable for a 0.13 mm ceramic coating. Later in the heating cycle, the stresses become tensile and exceed the tensile strength. This would lead to surface cracks. In the cooling cycle the stresses tend to reverse. The coating is thus subjected to stress peaks, stress reversals and inelastic behavior in each cycle, c.f., figures 1 and 2.

The nonlinear variation of stresses with heat transfer coefficient for the 0.38 mm ceramic coating is shown in figures 3(a) and (b). At higher values of h_g, the stresses are large and the coating could easily fail.

Radial stresses for various coating thicknesses at constant heat transfer coefficient are shown in figure 4. The calculation indicates that a dense 0.75 mm thermal barrier coating would fail and that a 0.50 mm coating would be marginal compared to coating attachment strength. The stress is a maximum near 1/2 second, diminishes with time and tends to reverse during cooling. No general parametric study was undertaken and, although thermophysical properties are very important, the minor variations found from changes to the input data did not significantly alter the results; thus 304 stainless or Rene' 41 results are about the same (see fig. 4.)

Stress control. - Since TBCs are susceptible to failure by thermal stress, stress control during manufacture and use of the thermal barrier coating is required. In manufacturing of TBCs, plasma spraying increases the temperature of the metal substrate. Since thermal expansion of ZrO_2 is less than that of the metal, undesirable compressive stresses result on cooling after coating. Therefore, cooling of the metal substrate during spraying might be beneficial.

Thermal stresses might also be controlled by cycle management during turbine service. Thermal stress is proportional to heat transfer, $\dot{Q}/A \sim h_g (T_{gas} - T_{surface})$. If the heat transfer coefficient and temperature are maintained below critical values during start-up, thermal stresses could be

kept below critical values. This could also be accomplished by integrated component/coating design techniques such as cooling air and coating thickness management.

CONCLUSIONS

Frequent thermal cycling of ZrO_2-8 w/o or 12 w/o Y_2O_3 TBCs over NiCrAlY on Rene' 41° to 1040° C sharply reduced coating life. Simplified and detailed stress calculations both showed that large thermal stresses which tend to detach the ceramic result from high initial rates of heat transfer such as those in the 0.3 Mach flame used in these experiments. These stresses were within the range of measured values of the adhesive/cohesive strength of the ceramic coating. These experiments and stress calculations show that repeatedly subjecting a ceramic coating to high rates of initial heating has a more destructive influence on the coating than sustained operation at temperature. The effect of such thermal compressive stresses might be minimized through coating deposition and thickness control and by turbine cycle management to keep starting heating rates below critical values.

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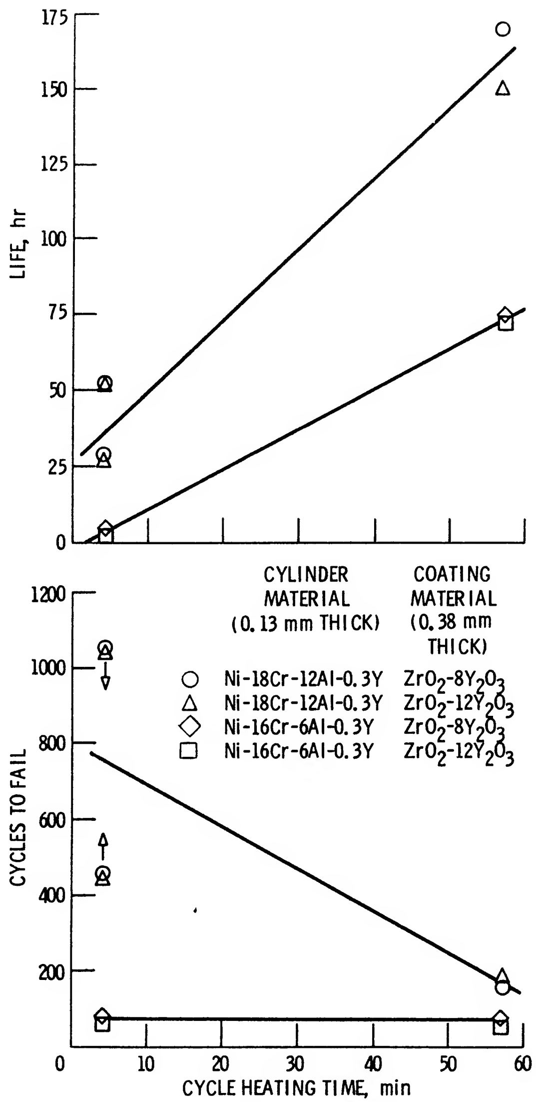


Figure 1. - Effect of cycling on life of thermal-barrier coating. Heating-cooling cycle: 4 min heat - 3 min forced cool; 57 min heat - 3 min forced cool. Optical surface temperature, 1040° C.

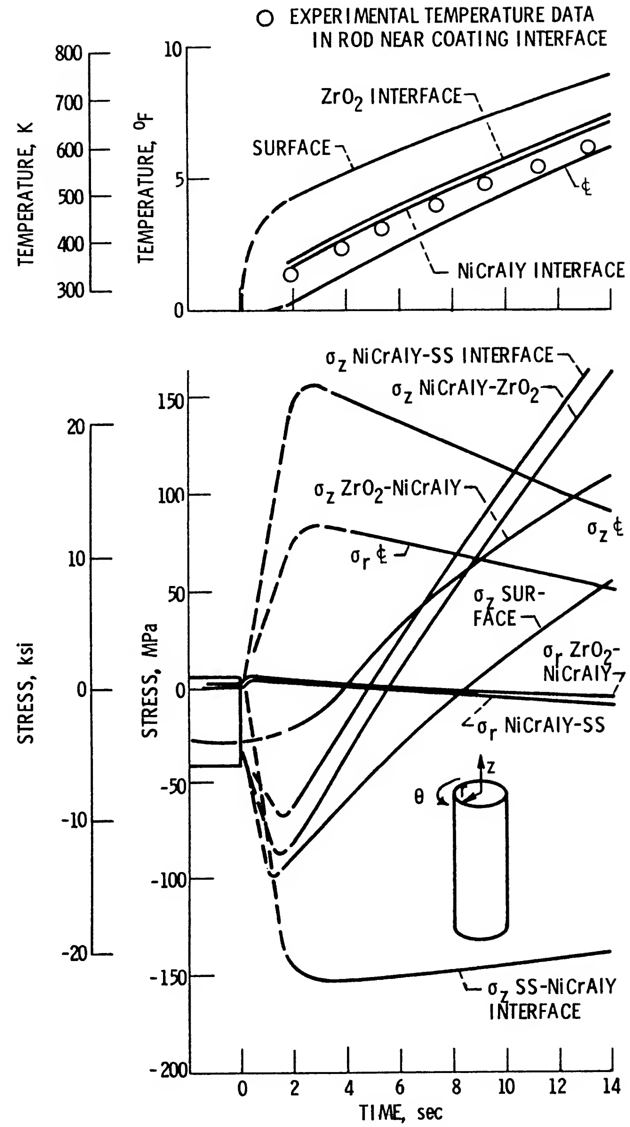
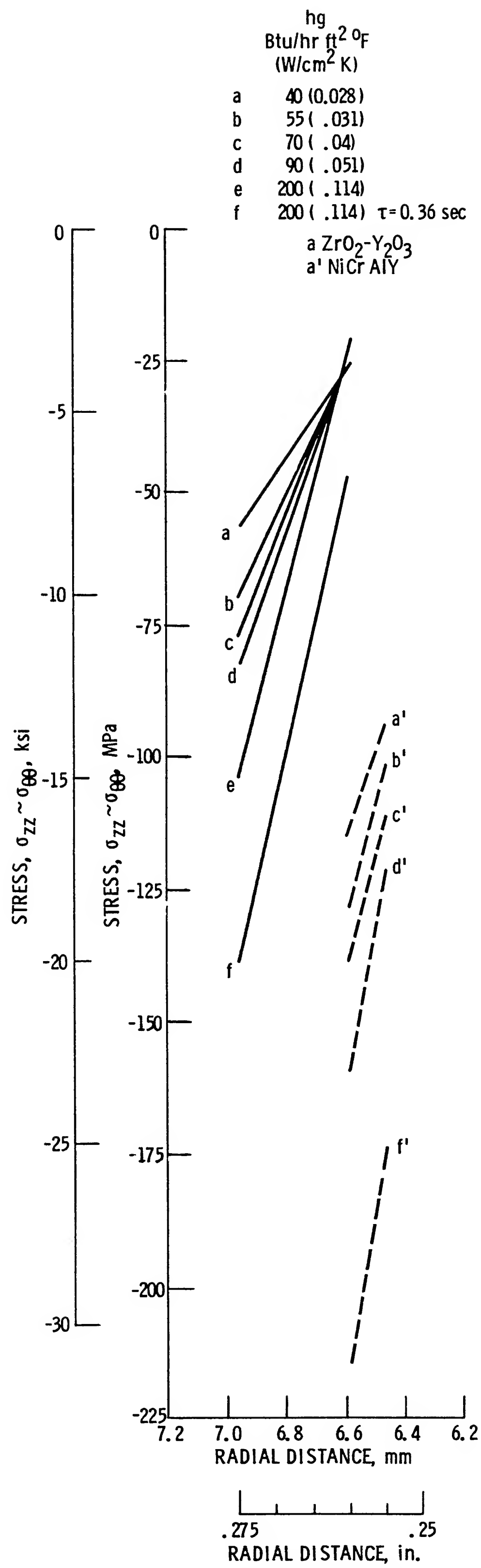
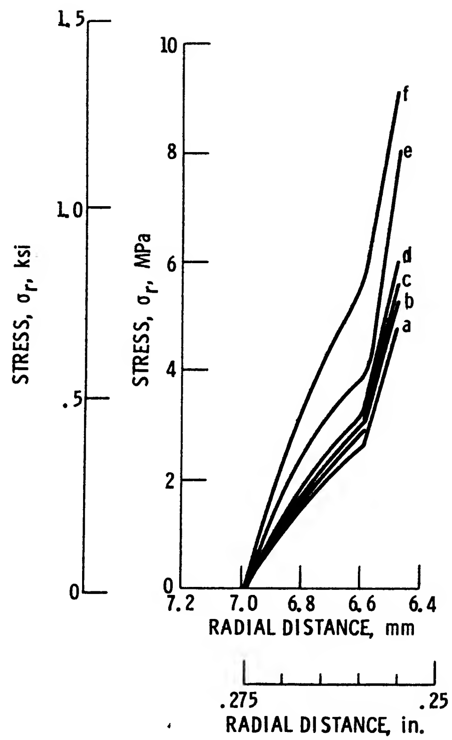


Figure 2. - Calculated temporal temperature and stress distribution in a thermal barrier coated cylinder. 0.38 mm of ZrO_2-Y_2O_3 over 0.13 mm of NiCrAlY bond coat. Cylinder diameter 13 mm.



(a) LONGITUDINAL OR HOOP STRESS.

Figure 3. - Calculated stresses for various heat transfer coefficients at τ = 1.8 sec.



(b) RADIAL STRESS.

Figure 3. - Concluded.

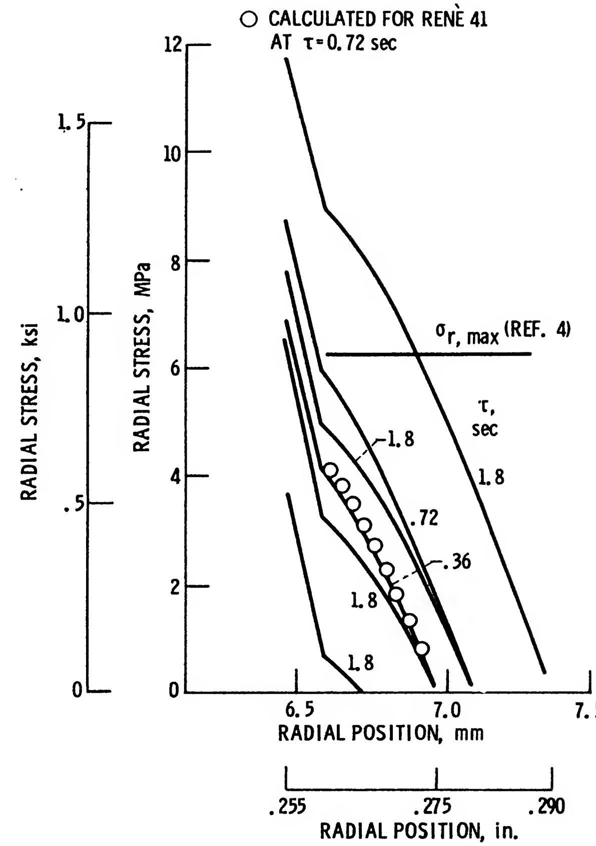


Figure 4. - Calculated variation of radial stress with coating thickness at τ = 1.8 sec and $\tau \rightarrow \tau_c$ for t = 0.38 mm and t = 0.51 mm.